CSG-1: MANUFACTURING A NEW POLYCRYSTALLINE SILICON PV TECHNOLOGY

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ABSTRACT

Crystalline Silicon on Glass (CSG) is a polycrystalline silicon PV (photovoltaic) technology that requires less than two micrometers of silicon thickness. At the time of this writing in April 2006, production of CSG solar panels is just beginning in a full-scale factory known as CSG-1. It was only 14 months ago, in February 2005, that ground-breaking for this factory occurred. At that time, the technology had only been demonstrated in 900-cm^2 laboratory samples. This article discusses some of the challenges faced in taking a new PV technology from R&D into production in such a short period of time. Photos of the equipment used for each of the key steps are shown and the experience of commissioning the process is discussed.

INTRODUCTION

CSG was developed from the outset to combine the proven advantages of crystalline silicon wafer-based technology with the manufacturing cost advantages of thin-film technology [1]. In April 2006, this technology demonstrated an aperture-area efficiency for a 95 cm^2 minimodule of 9.4% independently verified by Sandia National Labs. Total-area efficiencies for 1.4-m^2 modules exceeding 7% are anticipated in the first year of production, corresponding to a rated power of 100 watts. The production cost of these modules is about half that of wafer-based modules for factories of similar capacity. The CSG technology appears to be as durable as wafer-based approaches, and has the potential to be even better.

The employees who originally developed the CSG technology in Australia formed a new PV company in June 2004 called CSG Solar with the intent of commercializing the CSG technology. After an initial period of technology demonstration, a combination of private investment and government support was secured in December 2004 to build a factory in Germany to manufacture CSG modules. The factory, known as CSG-1, is located in the state of Saxony-Anhalt near Thalheim and has a rated annual capacity of 10 MW (Fig. 1). The first functional modules were produced in this plant in April 2006 and the workforce needed for continuous operation is currently being trained. Ramp-up of production to four shifts is expected by mid-year. The entire output of this plant for the first year and 80% of the output through 2010 has been sold in advance. Details of the shareholders and customers of CSG Solar are given on the company's website: www.csgsolar.com.

Fig. 1. CSG-1 factory offices and plant.

The factory building and support facilities are sized to allow the capacity of the factory to be doubled, requiring only the replication of some items of process equipment. Funding to expand the factory to an annual capacity of 20 MW was secured in June 2005 and that expansion is now underway. When the capacity expansion is complete later this year, the factory will be renamed CSG-2.

MANUFACTURING SEQUENCE

The manufacturing sequence used to produce CSG modules involves many PV industry firsts, starting with the glass superstrate material, which is borosilicate glass (BSG). BSG differs from the soda-lime glass used in most PV modules primarily in that it has a much lower thermal expansion coefficient. This makes it well suited for the high temperatures used in CSG manufacturing, and also makes the modules more durable. BSG plate glass is produced in limited quantities at present and represents about one-third of the total materials cost for a completed CSG module.

The photo in shows the factory's glass washer. There were two unexpected challenges encountered implementing this process. Much of the glass as-delivered has a rubbery residue on the surface caused by an interaction between the cutting oil and rubber gloves used to prevent fingerprints. A variety of detergents were tried until one was found that works adequately within the time allowed by the throughput requirement. Using this optimized wash cycle, the glass surface is so clean that it can hold a substantial electric charge. A corona discharge bar is used at the exit of the glass washer to remove this charge.

Fig. 2. Vitrododi glass washer.

The clean glass is textured using the Company's patented technique of coating it with a layer of half-micron silica beads. These beads are suspended in a liquid bath and the glass is dipped vertically into the bath in the apparatus shown in Fig. 3. The solution is mostly ethanol, hence the all-metal housing. The coating dries as the glass is withdrawn, but a subsequent belt bake is used to drive out any remaining water. The bead coating of pure silica is present on both surfaces and on the edges. This prevents the glass from sticking to its supports in subsequent high-temperature processing. This process has worked without much difficulty, one challenge being to understand how frequently to replenish the beads.

Fig. 3. Ramgraber texture coater.

The textured glass is coated with layers of silicon nitride and silicon in a PECVD deposition reactor (Fig. 4). This system was developed for the flat-panel display industry (Generation 5). The use of this commercially available equipment makes it possible to process large-area glass sheets (1.10 x 1.25 m^2) without incurring the very high cost and delay of developing specialized equipment for this purpose [2].

Fig. 4. Unaxis KAI-1200 PECVD.

The KAI-1200 processes 20 sheets of glass in a batch. Initially, these 20 sheets are loaded together into the input load lock. Half of the sheets are transferred as a group into one stack of ten deposition chambers. The other half are transferred as a group into a second stack of ten deposition chambers. This parallel processing improves throughput for a given investment in equipment. Nevertheless, this deposition system costs nearly as much as the rest of the factory's processing equipment combined. Thanks to years of experience in the flat-panel display industry, this equipment has proven to be reliable despite its complexity.

The silicon as-deposited is amorphous. Solid-phase crystallization is performed at 600ºC in batch ovens as shown in Fig. 5. Each oven holds a stack of 40 – 60 panels. Although crystallisation is a slow process, only a few ovens are needed because so many sheets can be loaded together.

Fig. 5. Nabertherm crystallisation ovens.

The crystallisation step produces a polycrystalline silicon material having an average grain size of about 1 µm [3]. During this step the panels change dramatically in color, from the blood red of a-Si to the golden hue of thin pc-Si. When viewed from the glass side, the panels continue to have a dark violet appearance due to the silicon nitride layer serving as an anti-reflection coating.

The oven crystallisation had previously been tested only with a few sheets in a stack. When tested in the factory with much thicker stacks, it was found that the delay for heating the sheets in the middle of each stack was much longer than expected. The thermal model used had failed to consider air gaps that develop between the sheets as a result of deformation that occurs during the heating cycle. A process with acceptable throughput was obtained only after a time-consuming optimization of the heating ramp rate, crystallisation temperature, and cooling rates. To improve the throughput further, additional ovens have been ordered for CSG-2. The extra space needed for these ovens was anticipated in the original factory design.

The silicon as-crystallized contains many crystallographic defects. These are annealed in the furnace shown in Fig. 6 by heating the glass briefly to over 900ºC. At this temperature, the glass requires a supporting 'setter'. In order to heat and cool the setter and glass quickly to obtain the desired throughput, the setter must have a low thermal mass, and thus can't be much thicker than the glass itself. The challenge is maximizing the number of times these setters can be reused without damage. An automated system has been installed that unloads the glass from the setter and returns the setter to the loading end of the furnace, where it is loaded with another sheet of glass, all with no manual handling. A few different setter materials have been evaluated, with various trade-offs between thickness, cost and durability. These need to be compared in continuous production conditions to select the one that is most appropriate.

Fig. 6. Tecnofimes roller furnace.

Like all pc-Si materials, CSG requires hydrogen passivation to maximize performance [4]. The amount of hydrogen required is much greater than for cast-ingot silicon. The equipment developed for this step is unique in that it accomplishes the required intense exposure to atomic hydrogen at temperatures above 600ºC using an in-line process for high throughput. The design of this Remote In-Line Passivation (RIPA) equipment, shown in Fig. 7, is the subject of a pending patent application. As expected for custom-designed equipment, significant time and effort has been needed to make this system operate reliably, but this has now been accomplished. The focus has shifted to optimizing the passivation process, which is affected by the width of the glass sheet due to the use of linear plasma sources to generate the atomic hydrogen.

Fig. 7. Roth & Rau hydrogen passivation.

Device fabrication utilizes a novel sequence protected by multiple patents [5,6] that starts with a pulsed infrared laser to slice the silicon layer into a series of discrete adjacent cells. In CSG-1 this process is done on the same laser system used to pattern the metal interconnect layer, to be described subsequently. A white resin layer is then applied using the roller coater shown in Fig. 8.

Fig. 8. Bürkle resin roller coater.

The resin layer is patterned using the industrial ink-jet printer shown in Fig. 9.

Fig. 9. Xennia ink-jet printer.

The first pass through the ink-jet printer creates openings in the resin where contact is to be made to the n^+ layer. To reach the buried n^+ layer, a patented silicon etch process is used to remove some of the silicon from within these openings, using the in-line tool shown in Fig. 10. The panel is then exposed to a solvent vapor that causes the resin to reflow just enough to protect the walls of the etched 'craters'.

Fig. 10. Schmid chemical etching.

A second pass through the ink-jet creates openings in the resin where contact is to be made to the surface p^+ layer. Another etch is used to remove damaged silicon from the surface within these 'dimple' openings, then a thin layer of aluminum is sputtered onto the surface using the equipment shown in Fig. 11. The metal contacts the n^+ and p^+ layers at the contact openings, but is otherwise isolated from the silicon by the resin layer.

Fig. 11. Von Ardenne aluminum sputter.

The pulsed infrared laser is used to remove the metal in an intricate pattern that separates the n^+ and p^+ contacts within each cell while connecting all of the p^+ contacts in one cell to the n^+ contacts in the adjacent cell. This step obtains high throughput despite the complexity of the pattern by using scanned pattern-projection optics while the panel is moving below.

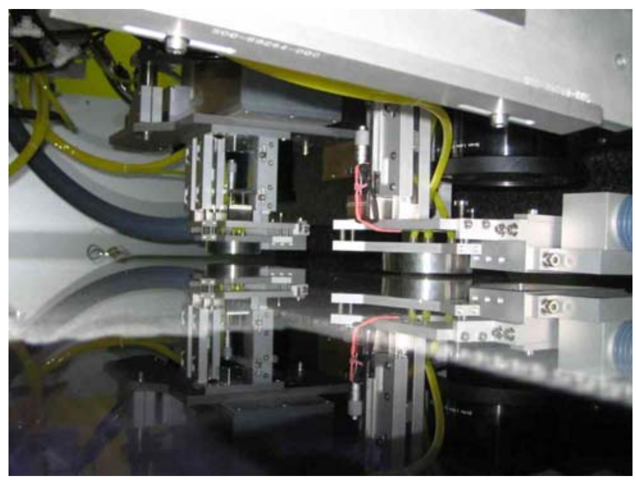

Fig. 12. Exitech four-head scanning laser.

Alignment of the patterns produced by the ink-jet and laser have proven to be the limiting factor in the schedule for ramp-up of CSG-1. These were the last two tools to be installed and the commissioning of these two tools continues as of this writing. Although the laser appears to be capable of meeting its performance expectations with further effort, the ink-jet tool appears unlikely to deliver its accuracy specifications. As an interim measure, the contact pattern has been redesigned with wider line spacing. This greatly relaxes the alignment tolerances, albeit with an associated increase in series resistance and some consequent loss in module power.

Bead blasting using the equipment shown in Fig. 13 removes all layers from the perimeter of the module to ensure safe operation up to 1000 volts.

Fig. 13. Olbricht edge isolation bead blaster.

Lead-free tabs are ultrasonically soldered along the two edges of the module and a polymer backsheet is laminated using the three-panel laminator shown in Fig. 14. A subsequent bake is used to ensure adequate cross-linking of the EVA that binds the backsheet to the panel.

Fig. 14. Meier laminator.

A junction box is attached and an aluminum frame fitted. The modules use only a single sheet of 3-mm glass, so they are quite lightweight for their size (13 kg for 1.4 m^2), but it is necessary to include an extra aluminum cross-beam on the back of the module to provide sufficient strength against wind loads. For installations where heavy snow loads are expected (5.4 kPa), two such cross-beams are used.

A flash test gives the illuminated I-V curve at four light intensities and allows each panel to be classified into performance bins with 5-watt increments. The completed modules from a given performance bin are then packaged for delivery to customers. A few of the first modules produced have been mounted in front of the factory offices, as illustrated in Fig. 15.

Fig. 15. CSG panels installed at the factory.

SUMMARY

This article has shared some of the experiences of taking a new PV technology from R&D into production in a short period of time. Despite the inclusion of several firsts for the PV industry, the commissioning of the process steps for the CSG technology has, for the most part, proceeded according to plan. Delays have occurred with those tools that were complex and first-of-a-kind, and some of these delays have stretched to several months. Such is the nature of manufacturing any new technology. Fortunately, it has been possible to modify the process to accommodate the limitations presented by these late tools, so that production can commence.

REFERENCES

[1] P.A. Basore, "Pilot production of crystalline silicon on glass modules," *29th IEEE PVSC*, New Orleans, May 2002, pp. 49-52.

[2] P.A. Basore, "Large area deposition for crystalline silicon on glass modules," *3rd World Conference on Photovoltaic Energy Conversion*, Osaka, May 2003, pp. 935-938.

[3] M.A. Green, et al, "Crystalline silicon on glass (CSG) thin-film solar cell modules," *Solar Energy*, **77**, 2004, pp. 857-863.

[4] M.J. Keevers et al., "Remarkably effective hydrogenation of crystalline silicon on glass modules," *20th European PVSEC*, Barcelona, June 2005, pp. 1305-1308.

[5] P.A. Basore, "Simplified processing and improved efficiency of crystalline silicon on glass modules," *19th European PVSEC*, Paris, June 2004, pp. 455-458.

[6] P.A. Basore, "Crystalline silicon on glass device optimization," *31st IEEE PVSC*, Lake Buena Vista, January 2005, pp. 967-970.